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PROCESS MINERALOGY OF SAMPLES FROM THE WELLGREEN Cu-Ni-Pt-Pd DEPOSIT, YUKON

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by

L.J. Cabri*, J.H.G. Laflamme* and R. Lastra*

EXECUTIVE SUMMARY

The mineralogy of samples from the Wellgreen Cu-Ni-Pt-Pd deposit, Yukon Territory, is complex and the metals of interest are contained within fine-grained minerals which vary in size and mineral associations from sample to sample.

The major Ni carriers are pentlandite and violarite; the major Cu carrier is chalcopyrite. About 70% of the major Ni carriers and 78% of the Cu carrier will be liberated at a grind of 80% -26.7 μm (-500 mesh) for sample #1. For samples #2 and #3, the liberation would be 71% and 65% for Ni, 74% and 60% for Cu, respectively. Fine grinding, however, cannot liberate the Ni contained in silicates and pyrrhotite, estimated to total 24.5% for typical low-grade gabbro (West zone, sample #1), 15% for typical "clinopyroxenite" (West zone, sample #2), and 12% for typical "clinopyroxene-rich peridotite" (East zone, sample #3).

The principal Pt carrier (sperrylite) varies considerably in grain-size between samples and fine grinding, required to liberate the major Ni and Cu carriers, may be counterproductive in samples where sperrylite is relatively coarse-grained, as some would then be unrecovered (e.g. sample #1). In addition, sperrylite in samples #2 and #3 is closely associated with magnetite.

Palladium occurs in diverse ways. It occurs in the form of several Pd minerals (e.g. sudburyite, testibiopalladite, merenskyite), as a replacement for Ni in several tellurides,

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antimonides and tellurantimonides (e.g. melonite), as well as in very low concentrations in pentlandite (up to 34 ppm), chalcopyrite (up to 9 ppm), and pyrrhotite (up to 5.6 ppm). Palladium minerals and Pd-bearing minerals are strongly associated with chalcopyrite in sample #1 and will thus report to a Cu concentrate. However, 22% of the total Pd is in solid solution in pentlandite and will thus report to the Ni concentrate. In the other two samples, less Pd occurs in solid solution in pentlandite, and the PGM are distributed mainly among pentlandite, chalcopyrite, and magnetite in sample #2, and among pentlandite, pyrrhotite, chalcopyrite, and magnetite in sample #3. Therefore, the feasibility of magnetic concentration should be investigated for samples like #2 and #3, in order to improve Pt and Pd recoveries.

Rhodium was found to occur as rare hollingworthite, in rare cobaltite (up to 2.7%) and, by proton microprobe analyses, in low concentrations in chalcopyrite (to 10 ppm) and pentlandite (to 12 ppm). Iridium occurs in rare hollingworthite (up to 7.8%) and very rarely as the native metal or in an undefined Re-Ir-Os-Ru alloy. Ruthenium was determined by proton microprobe analyses to occur in pentlandite (up to 13 ppm) and chalcopyrite (up to 10 ppm), in addition to rare laurite and Re alloy.

Keywords: Wellgreen deposit, Yukon, platinum, palladium, copper, nickel, mineralogy, process mineralogy, liberation.

INFORMATION COMMERCIALE PROTÉGÉE

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MINÉRALOGIE INDUSTRIELLE D'ÉCHANTILLONS PROVENANT DU GISEMENT DE Cu-Ni-Pt-Pd WELLGREEN, AU YUKON

par

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RÉSUMÉ

Des échantillons provenant du gisement de Cu-Ni-Pt-Pd Wellgreen, au Yukon, ont une minéralogie complexe, et les métaux d'intérêt sont contenus dans des minéraux à grain fin dont la grandeur et les associations varient d'un échantillon à l'autre.

La pentlandite et la violarite sont les principaux minéraux de Ni, tandis que la chalcopyrite est le principal minéral de Cu. Pour l'échantillon n° 1, environ 70 % des principaux minéraux de nickel et 78 % du minéral de cuivre seront libérés par un broyage à 80 % de -26,7 μm (maille de 500). Dans le cas des échantillons n°s 2 et 3, le taux de libération sera de 71 % et de 65 % pour le Ni et de 74 % et de 60 % pour le Cu, respectivement. Or, le broyage fin ne libère pas le Ni contenu dans les silicates et la pyrrhotite, qui représente au total 24,5 % pour le gabbro typique de faible métamorphisme (zone ouest, échantillon n° 1), 15 % pour la «clinopyroxénite» typique (zone ouest, échantillon n° 2) et 12 % pour la «péridotite typique, riche en clinopyroxène» (zone est, échantillon n° 3).

La granulométrie du principal minéral platinifère (sperrylite) varie considérablement d'un échantillon à l'autre; or, le broyage fin qui est requis pour la libération des principaux minéraux de Ni et de Cu pourrait constituer une entrave dans les échantillons où la sperrylite est relativement grossière, car une partie du métal ne serait pas récupérée (p. ex., échantillon n° 1). En outre, la sperrylite est étroitement associée à la magnétite dans les échantillons n°s 2 et 3.

Le palladium se rencontre sous diverses formes, soit sous la forme de minéraux de Pd (p. ex., sudburyite, testibiopalladite, mérenskyite), comme remplacement du Ni dans plusieurs tellurides, antimoniures et tellurantimoniures (p. ex. melonite), et en concentrations très faibles dans la pentlandite (jusqu'à 34 ppm). la chalcopyrite (jusqu'à 9 ppm) et la pyrrhotite (jusqu'à 5,6 ppm). Les minéraux de palladium et les minéraux palladifères sont fortement associés à la chalcopyrite dans l'échantillon n° 1 et, par conséquent, ils s'accumuleront dans un concentré de Cu. Toutefois, 22 % de tout le Pd se trouve en solution solide dans

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dans la pentlandite et s'accumulera donc dans le concentré de Ni. Dans les deux autres échantillons, il y a moins de Pd en solution solide dans la pentlandite et les platinoïdes pourraient se répartir également entre la pentlandite, la pyrrhotite, la chalcopyrite et la magnétite (échantillon n° 2) ou entre la pentlandite, la pyrrhotite, la chalcopyrite et la magnétite (échantillon n° 3). Par conséquent, il faudrait examiner la possibilité d'utiliser la concentration magnétique pour améliorer la récupération de Pt et de Pd dans les échantillons comme les n°s 2 et 3.

Le rhodium se présente dans la hollingworthite (rare), dans la cobaltite (rare) (jusqu'à 2,7 %) et, d'après des analyses par microsonde à protons, en faibles concentrations dans la chalcopyrite (jusqu'à 10 ppm) et la pentlandite (jusqu'à 12 ppm). L'iridium se rencontre dans la hollingworthite (rare) (jusqu'à 7,8 %) et très rarement sous la forme de métal à l'état natif ou d'alliage non défini de Re-Ir-Os-Ru. L'analyse par microsonde à protons révèle que le ruthénium se présente dans la pentlandite (jusqu'à 13 ppm) et la chalcopyrite (jusqu'à 10 ppm), de même que dans la laurite (rare) et un alliage de Re.

Mots clés : cuivre, gisement de Wellgreen, libération, minéralogie, minéralogie industrielle, nickel, palladium, platine, Yukon

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INTRODUCTION

A total of eight samples from the Wellgreen deposit were received from Archer, Cathro & Associates (1981) Limited, Vancouver. The first five samples (Phase I) consisted of drill core rejects and were studied to determine the mineralogy, in particular the mineralogy of the platinum-group elements (PGE). The second series of 3 samples (Phase II) consisted of drill core and were considered representative of certain portions of the Wellgreen deposit. The latter samples were studied mineralogically to provide guidance for mineral processing and a base for consideration of metallurgical options.

LOCATION AND HISTORY

The Wellgreen deposit is located in the Kluane District of the Yukon, 315 km northwest of Whitehorse and 14 km to the west of the Alaska Highway. The deposit was discovered in 1952 by Mr. Wellington Green, a prospector, and subsequent exploration delineated 669,150 tonnes grading 2.04% Ni, 1.42% Cu, 0.038 oz/ton Pt, 0.027 oz/ton Pd and 0.005 oz/ton Au (Hulbert et al., 1988). The deposit was mined in 1972-73 with the total production amounting to 189,211 tons of ore. In recent years there has been renewed interest in the deposit, with a particular emphasis on the PGE content.

GEOLOGIC SETTING

The Wellgreen deposit occurs in the Quill Creek complex, which is one of a number of Triassic intrusive bodies emplaced in Permo-Triassic volcanic and sedimentary rocks of the Kluane Ranges (Campbell, 1960; 1977). The Quill Creek complex is thought to be 16 km long and 600 m wide. It has been intensely faulted and possibly folded, and the ultramafic members of the complex have been variably serpentinized. The rocks vary from gabbroic at the margins to peridotites and dunites (Hulbert et al., 1988). Four main zones of PGE-enriched

mineralization have been outlined: East zone, West zone, North zone, and Northwest zone (All-North Resources Ltd., Ann. Rept., 1987).

SAMPLES AND METHOD OF ANALYSIS

All eight samples studied are listed in Table 1 with the descriptions provided by Archer, Cathro & Associates (1981) Limited (ACA). Phase I samples were drill-core rejects and consisted of 4 to 14 sub-samples with assay values for Cu, Ni, Pt, Pd and Au provided by ACA (Table 2). The sub-samples were from different drill-core intervals and also from different drillholes; hence a range of values is given for each element analyzed. Sample DI consists of 3 sub-samples derived from an original set of 14, selected on the basis of their higher metal concentrations. Sample EII is one of seven sub-samples from sample E, selected on the basis of a much higher Ni value; the remaining 6 sub-samples are called EI. Phase II samples were selected by us (on instructions from ACA) from drill-core shipped to Ottawa. These consisted of the remaining drill-core splits for various selected intervals.

Table 1. Samples studied

Sample		Description
A	Phase I	Massive sulphide - East zone
B	Phase I	Semi-massive sulphide in chill gabbro - East zone
DI	Phase I	Disseminated sulphides in peridotite - West zone
EI	Phase I	Disseminated sulphides in chill gabbro/pegmatitic gabbro - West zone
EII	Phase I	Disseminated sulphides in chill gabbro/pegmatitic gabbro - West zone
1 (a)	Phase II	Typical low-grade gabbro - West zone
2 (b)	Phase II	Typical clinopyroxenite - West zone
3 (c)	Phase II	Typical clinopyroxene-rich peridotite - East zone
(a) DDH137 (164.1 - 169.1 m); (b) DDH137 (118.11 to 122.85 m + 129.50 to 130.76 m); (c) DDH98 (83.82 to 87.17 m)		

Assay results for these samples are also given in Table 2. Two additional samples were studied, in part: a drill core sample (88-139) at 236-87 m, described as disseminated net-textured sulphide (DNTS) and, a grab underground sample from stope 42-01, consisting of massive sulphide (WG-1).

Table 2. Assay results

Sample	Cu%	Ni%	Co%	Pt g/t	Pd g/t	Au g/t
A	0.84-2.00	1.71-4.90	N/A*	1.54-4.12	1.41-4.12	N/A
B	0.56-1.56	0.70-2.96	N/A	0.55-2.30	0.55-2.92	N/A
DI	1.51-4.25	1.62-2.54	0.08-0.13	3.46-5.59	0.96-2.57	0.24-0.34
EI	0.67-1.57	0.26-0.69	0.02-0.04	1.41-2.95	0.41-0.99	0.10-0.51
EII	0.63	2.52	0.08	1.99	1.44	<0.069
1	0.435	0.18	N/A	0.375	0.21	0.034
2	0.27	0.305	N/A	0.59	0.39	0.145
3	0.145	0.40	N/A	0.29	0.45	0.031

Assay results for samples A, B, DI, EI and EII were provided by Archer, Cathro & Associates; for samples 1 to 3: Cu, Ni were done by Bondar-Clegg (Ottawa), and Pt, Pd and Au by Activation Laboratories (Brantford).
*N/A: not available.

After crushing and grinding to -48 or -65 mesh, the samples were carefully mixed, and 300-500 g splits were used for sizing. The -65 +100 mesh, -100 +200 mesh and -200 +270 mesh fractions were subjected to heavy liquids, magnetic separations and elutriating tube to provide small quantities of sulphide concentrates for detailed mineralogical investigation by reflected light microscopy, scanning electron microscopy and electron microprobe analysis. Size distributions by image analysis of the three Phase II samples were done on -35 +65, -65 +100 and -100 +200 mesh fraction. The sample preparations for Phase I and II are given in Figure 1. Most sulphides were also analyzed for trace elements with the Guelph Proton Microprobe; some with the HIAF Proton Microprobe in North Ryde, Australia. In addition, some float products were submitted for identification by X-ray diffractometry.

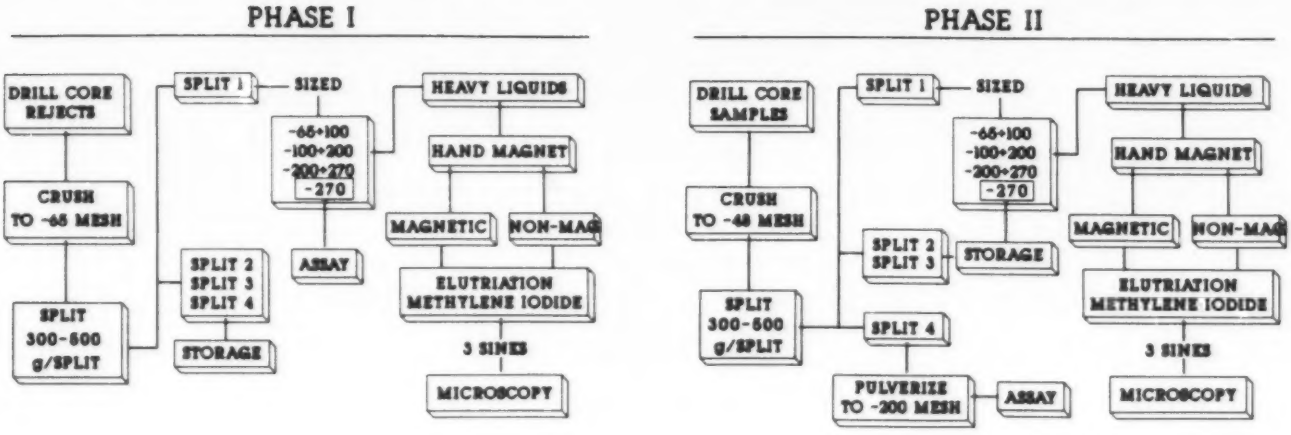

Fig. 1. Sample preparation flow sheets for Phases I and II.

RESULTS

(a) Mineralogy

The opaque minerals (including PGM and PGE-bearing minerals) vary considerably from sample to sample. An approximate relative order of abundance for major opaques is pyrrhotite, pentlandite, chalcopyrite, pyrite, magnetite and ilmenite (Table 3). However, even this order can vary, e.g., in sample #3 magnetite is a major component. The less common to rare opaque minerals are also listed in Table 3. The platinum-group minerals (PGM) and PGE- and Re-bearing minerals are listed in Table 4, approximately in decreasing relative abundance. As is the case for the major opaques, the relative abundance can vary significantly from sample to sample.

Sample A (Massive sulphide, East zone)

Pyrrhotite and pentlandite are the major opaque minerals in this sample, followed by chalcopyrite, pyrite and magnetite. Occurring in trace amounts are cobaltite/gersdorffite, arsenopyrite, ullmannite, chromite, violarite, galena, Au-Ag alloy and altaite.

Electron microprobe analyses of fifteen grains of pentlandite selected at random show very little variation with average contents of 35.5 (34.8-36.0) wt% Ni and 1.3 (1.2-1.5) wt% Co. Cu and Pd were not detected (MDL's of 0.03 and 0.025 wt% respectively). Twenty randomly selected grains of pyrrhotite had a range of 0.37 to 1.2 wt% Ni and averaged 0.81 wt% Ni. Fourteen of these grains were of the hexagonal variety, while six were of the monoclinic variety.

One hundred and forty-six discrete grains of PGM were identified in this sample, all of them are relatively small in size (largest 12x30 μm); more than 90 vol.% occurring in pyrrhotite. The distribution of these PGM among four host minerals is shown in Figure 2. Seventy-two of these grains are merenskyite (<2 to 10x15 μm in size), of which thirty-one were quantitatively analyzed and have average contents of 8.0 (0.16-19.0) wt% Pt and 3.9 (1.3-7.4) wt% Ni as replacement for Pd, and 10.7 (2.4-18.6) wt% Bi and 1.1 (n.d.-11.2) wt% Sb as replacement for Te. Thirty-three grains of moncheite were found, <2 to 4x5 μm in size. Eighteen of these grains were quantitatively analyzed and have average contents of 7.8 (2.7-11.8) wt% Pd and 3.2 (1.5-4.8) wt% Ni as replacement for Pt and 8.1 (n.d.-12.8) wt% Bi, as well as trace amounts of Sb and As, as replacement for Te. Six grains of sperrylite, which are relatively coarser in size (6x10 to 12x30 μm), were observed; 97 vol.% of which were found in pyrrhotite, and 3 vol.% in pentlandite. Twenty-eight grains of sudburyite (<2 to 3x6 μm) were found, of which 94 vol.% occur in pyrrhotite, and 6 vol.% in cobaltite/gersdorffite. Also found in pyrrhotite, are seven grains of testibiopalladite (<2 to 6x14 μm in size) which contain up to 12.6 wt% Pt as replacement for Pd. Finally, three grains of Pd-Pt-bearing melonite (2x4 - 4x10 μm) were observed in pyrrhotite, with Pd varying between 2.9 and 10.5 wt%, whereas Pt was found in two grains with values of 1.8 and 6.9 wt%. Only one small inclusion of a Au-Ag alloy was found in cobaltite/gersdorffite.

Table 3. Opaque minerals observed in samples from Wellgreen

Major Minerals			
pyrrhotite	Fe_7S_8-Fe_9S_{10}*	pyrite	FeS_2
pentlandite	$(Fe,Ni)_9S_8$	magnetite	Fe_3O_4
chalcopyrite	$CuFeS_2$	ilmenite	$FeTiO_3$
Less Common to Rare Minerals			
violarite	$FeNi_2S_4$	galena	PbS
sphalerite	(Zn,Fe)S	altaite	PbTe
chromite	$FeCr_2O_4$	nickeline	NiAs
cobaltite**	CoAsS/NiAsS	undefined	Cu-Fe-Ba-S†
arsenopyrite	FeAsS	covellite	CuS
ullmannite	NiSbS	breithauptite	NiSb
siegenite	$(Ni,Co)_3S_4$	barite	$BaSO_4$
argentopentlandite	$Ag(Fe,Ni)_8S_8$	titanite	$CaTiSiO_5$
gold/electrum	(Au,Ag)	hessite	Ag_2Te
melonite	$NiTe_2$	matildite(?)	$AgBiS_2$
bismuth telluride(s)	Bi-Te(?)		

* ideal formula given for all minerals
** unidentified members of the cobaltite-gersdorffite series
† probably a new Cu-Fe-Ba sulphide.

Table 4. PGM and PGE- and Re-bearing minerals observed at Wellgreen

PGM in relative order of abundance			
sperrylite	$PtAs_2$	undefined	$(Pd,Ni)_2(Te,Sb)_3$
sudburyite	PdSb	undefined	$(Pd, Ni)_3(Te,Sb)_4$
testibiopalladite	PdSbTe	undefined	Pd(Bi,Te)
merenskyite	$PdTe_2$	undefined	$Pd_3Ni(Sb,Te,Bi)_5$
moncheite	$PtTe_2$	laurite	RuS_2
michenerite	PdBiTe	kotulskite	PdTe
stibiopalladinite	Pd_5Sb_2	Pt-Fe alloy(s)	Pt_3Fe or PtFe(?)
mertieite II	Pd_8Sb_3	undefined	Re > Ir > Os > Ru alloy
geversite	$PtSb_2$	undefined	Pd-Hg
hollingworthite	RhAsS	iridium	Ir
froodite	$PdBi_2$	undefined	Re sulphide(?)
PGE-bearing minerals			
melonite	$(Ni,Pd,Pt)Te_2$	up to 15.1% Pd; up to 9.37% Pt	
undefined	$(Ni,Pd)_2(Te,Sb)_3$	up to 22.8% Pd	
undefined	$(Ni,Pd)_3(Te,Sb)_4$	up to 15.9% Pd	
breithauptite	(Ni,Pd)Sb	up to 18.9% Pd	
hexatestibiopanickelite	$(Ni,Pd)_2SbTe$	up to 15.9% Pd	
ullmannite	(Ni,Pd)SbS	up to 0.09% Pd	
cobaltite	(Co,Rh)AsS	up to 2.7% Rh, in zones	
pentlandite	(Pd,Rh,Ru)†	up to 34 Pd, 12 Rh, 13 Ru (ppmw)	
chalcopyrite	(Ru,Rh,Pd)†	up to 10 Ru, 10 Rh, 9 Pd (ppmw)	
pyrrhotite	(Pd)†	up to 5.6 ppmw Pd	
†trace levels as determined by proton microprobe.			

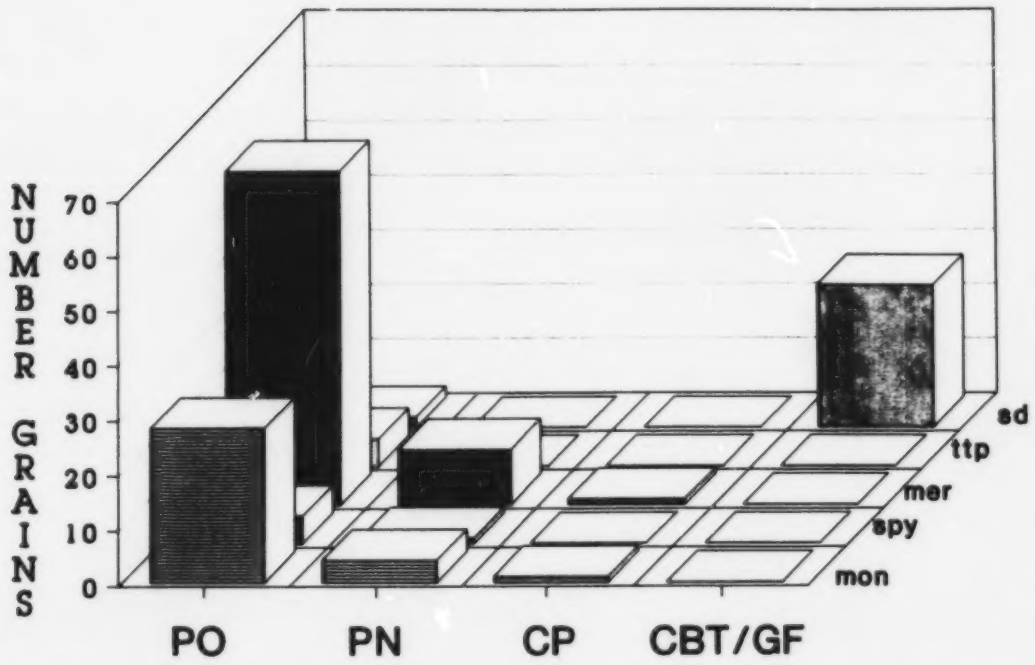

Fig. 2. Distribution of 146 PGM grains included in pyrrhotite (PO), pentlandite (PN), chalcopyrite (CP), and cobaltite/gersdorffite (CBT/GF). Sample A, massive sulphide.

Sample B (Semi-massive sulphide in chill gabbro, East zone)

The opaque minerals observed in this sample are basically the same as those reported for sample A, with the exception that magnetite was not obvious in this case. Unfortunately, due to problems experienced during polishing of the heavy mineral separates, the polished sections examined may not be truly representative. Nevertheless, nine coarse grains of sperrylite were found, ranging in size between 15x75 and 70x110 μm and, in addition, all grains were either totally liberated (61 vol. %) or with minor chalcopyrite and pyrrhotite attached (39 vol. %).

Eleven grains of testibiopalladite were observed (<2 to 10x15 μm in size) of which 95 vol. % were found included in pyrrhotite and 5 vol. % in chalcopyrite. Nine of these grains were quantitatively analyzed, and have average contents of 0.14 wt% Pd and 1.8 wt% Ni as substitution for Pd, and an average of 4.0 (0.41-8.0) wt% Bi as replacement for Sb.

Also, seven small grains of sudburyite were found in nickeline (63 vol.%) and in cobaltite/gersdorffite (37 vol.%); they range in size between <2 to 3x6 μm. Two small grains of merenskyite (1x2 and 3 μm) were observed in pyrrhotite, one shows 1.8 wt% Pt as replacement for Pd, two <2 μm inclusions of geversite and a 4x6 μm grain of moncheite were also found in pyrrhotite. Finally, two grains of an undefined $(Ni,Pd)_2(Te,Sb)_3$ mineral were observed, one in pyrrhotite, the other in pentlandite, and one grain of Pd-Pt-bearing melonite was also found in pyrrhotite.

Sample D1 (Disseminated sulphides in peridotite, West zone)

Pyrrhotite and pentlandite are once again the major opaque minerals, followed by chalcopyrite and magnetite. Occurring in much smaller amounts are pyrite, cobaltite/gersdorffite, an undefined Cu-Fe-Ba sulphide mineral, arsenopyrite, ilmenite, chromite, galena, hessite, Au-Ag alloy and argentopentlandite.

Electron microprobe analyses of fifteen randomly selected grains of pentlandite show little variation, with average contents of 33.6 (33.2-33.9) wt% Ni and 1.8 (1.6-2.3) wt% Co. Twenty grains of pyrrhotite, selected at random were also analyzed and had a range of 0.37 to 0.59 wt% Ni and averaged 0.49 wt%. Cobalt was not detected (MDL of 0.03 wt%). All of these grains proved to be the hexagonal variety.

Two hundred and thirty-eight PGM grains were observed in this sample; their distribution is given in Figure 3. Eighty-six of these grains, measuring between <2 and 30x65 μm, are sperrylite, of which 66 vol.% occur in magnetite, 29 vol.% in chalcopyrite, 5 vol.% in pyrrhotite and 1 vol.% in gangue. Seventy-one grains of sudburyite (<2 to 60x60 μm in size) were identified, of which 79 vol.% are included in gangue, 14 vol.% in magnetite, 5 vol.% in chalcopyrite and 1 vol.% in pyrrhotite.

Microprobe analyses of the sudburyite shows up to 3.1 wt% Ni as replacement for Pd and up to 22.2 wt% Te and 11.2 wt% Bi as replacement for Sb. Twenty-nine grains of moncheite were also identified (<2 to 5x10 μm in size). Thirteen of these grains were quantitatively analyzed, and have minor substitution of Pd (n.d.-2.3 wt%) and Ni (n.d.-3.7 wt%) for Pt; Bi (n.d.-17.5 wt%) and Sb (n.d.-0.89 wt%) for Te: 90 vol.% are included in pyrrhotite,

9 vol. % in magnetite and 1 vol. % in chalcopyrite. Eleven grains of michenerite were observed, (2x4 and 15x25 μm in size), 83 vol. % of which are included in magnetite, 14 vol. % in gangue, 2 vol. % in pyrrhotite and 1 vol. % in chalcopyrite. Seventeen grains of kotulskite (< 1 to 10x10 μm) that have up to 27.1 wt% Bi and 14.7 wt% Sb as replacement for Te were also identified; 87 vol. % of which are included in magnetite and 13 vol. % in pyrrhotite. Magnetite is also the host mineral for ten grains of mertieite II (< 1 to 4x11 μm), eight grains of stibiopalladinite (< 1 to 3x8 μm), three grains of an undetermined Pd(Bi,Te) mineral (3x5 to 5x15 μm), one grain of geversite (6x8 μm) and finally, one grain of an undetermined $Pd_3Ni(Sb,Te,Bi)_2$ mineral measuring 12x40 μm across. Also, one grain of another undetermined $(Pd,Ni)_3(Te,Sb,Bi)_4$ mineral (5x10 μm) was observed in pyrrhotite. Three grains of Au (or Au-Ag alloy) were found, one liberated (30x45 μm), one occurring in pyrrhotite (15x100 μm) and the third included in magnetite (15x25 μm).

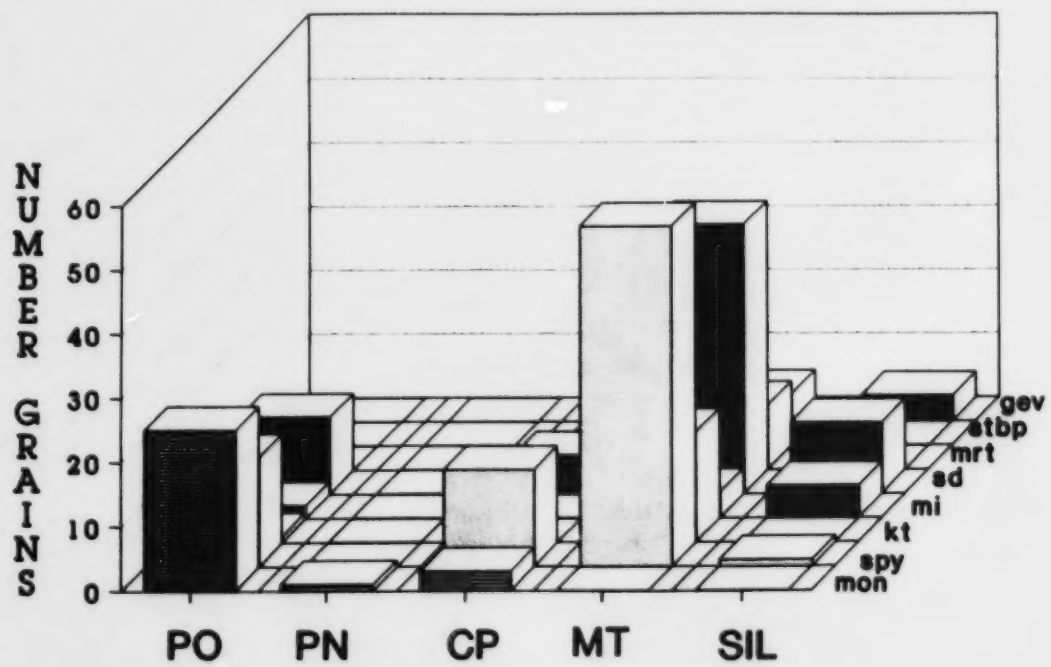

Fig. 3. Distribution of 238 PGM grains included in pyrrhotite (PO), pentlandite (PN), chalcopyrite (CP), magnetite (MT) and silicates (SIL). Sample D1, disseminated sulphides in peridotite.

Sample EI (Disseminated sulphides in chill gabbro/pegmatitic gabbro, West zone)

The mineralogy of this sample has been reported by Cabri and Laflamme (1988) and will not be repeated here, except for a few important highlights. The volume percent distribution of the PGM and palladian melonite is shown in Figure 4. A total of 239 discrete PGE or PGE-bearing grains were found of which 187 were coarse-grained sperrylite (5x10 to 145x145 μm). In addition, because the sperrylite is relatively so coarse-grained, a significant percentage (66 vol.%) is liberated within the size fractions studied. The other PGM found were michenerite (10 grs.), testibiopalladite (4 grs.), merenskyite (4 grs.), froodite (2 grs.), and sudburyite (1 gr.). Pd-bearing melonite (5.5 to 15.1 wt.% Pd) is common (31 grs.) as are 33 grains of gold/electrum (<2 to 70x110 μm) in size. As discussed later, this sample is considered anomalous, in comparison to the other samples studied.

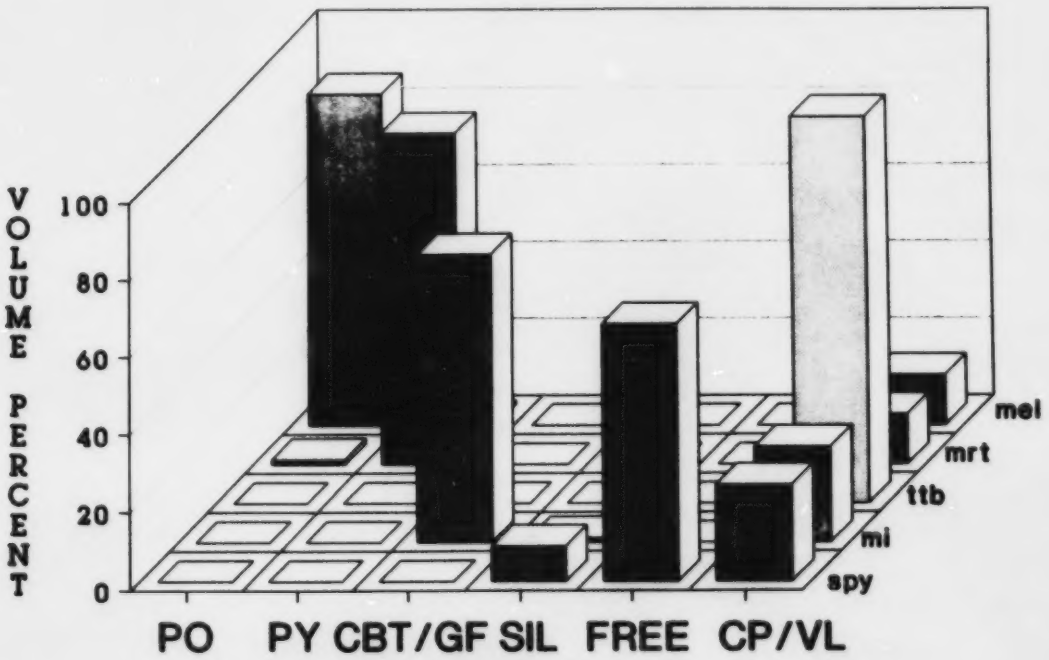

Fig. 4. Volume per cent distribution of PGM and palladian melonite in different host minerals or liberated. PO=pyrrhotite, PY=pyrite, CP/VL=chalcopyrite/ violarite, CBT/GF=cobaltite/ gersdorffite, and SIL=silicates. Sample EI, disseminated sulphides in chill gabbro.

Sample EII (Disseminated sulphides in chill gabbro/pegmatitic gabbro, West zone)

Pyrrhotite and pentlandite are the major opaque minerals in this sample, with minor quantities of pyrite, cobaltite/gersdorffite, arsenopyrite, ullmannite, chalcopyrite, nickeline, violarite, chromite, sphalerite, magnetite and argentopentlandite. Trace amounts of breithauptite, covellite, marcasite, galena, rutile, Au-Ag alloy and an undefined Cu-Fe-Ba sulphide were also found.

Electron microprobe analyses of the major Ni-bearing mineral pentlandite, show very little variation; the average of twelve grains selected at random, have 35.2 (34.5-35.9) wt% Ni and 1.5 (1.3-1.8) wt% Co. Cu and Pd were not detected at minimum detection levels of 0.035 and 0.03 wt% respectively. Twenty grains of randomly selected pyrrhotite were also analyzed, and have average contents of 0.60 (0.27-0.89) wt% Ni and 0.025 (<0.03-0.04) wt% Co; twelve of these grains are of the hexagonal variety. Cu was not detected (MDL = 0.035 wt%).

Eighty-six discrete PGM or PGE-bearing grains were found in this sample, excluding grains of Pd-bearing breithauptite. Twenty-one are sperrylite, and they range from <2 to 40x55 μm; 99 vol.% were observed associated with or included in silicate gangue and 1 vol.% included in pyrrhotite. Thirty-seven grains of an undefined $(Ni,Pd)_2(Te,Sb)_3$ mineral were identified; they range between <2 to 12x22 μm and the analyses of twenty-two of these grains have an average content of 13.1 (5.5-20.7) wt% Pd. One of these grains has Pd in excess of Ni, which suggests a possible solid solution series between $(Ni,Pd)_2(Te,Sb)_3$ and $(Pd,Ni)_2(Te,Sb)_3$. All of these grains are closely associated with pyrrhotite, as they either occur as inclusions in pyrrhotite or in sulpharsenides, themselves either attached or completely enclosed in pyrrhotite.

Nineteen grains of melonite were found (<2 to 5x8 μm in size); 97 vol.% of which are included in pyrrhotite, 0.3 vol.% in cobaltite, itself included or associated with pyrrhotite, and 2.5 vol.% in pentlandite. Eight of these grains were quantitatively analyzed and gave Pd contents of 3.4 to 11.9 wt%, and Pt contents of <0.10 to 9.3 wt%. The four grains of testibiopalladite identified (3 to 6x10 μm in size), are all closely associated with pyrrhotite, or cobaltite and gangue. Four grains of sudburyite were also found, they range in size between <2 to 4x5 μm; 87 vol.% of these grains are occurring in cobaltite/gersdorffite and 13 vol.% in

ullmannite. The volume per cent distribution of these PGM and Pd- and Pt-bearing melonite is shown in Figure 5.

Several grains of Pd-bearing breithauptite were found, generally <40 μm in size, and associated with ullmannite and cobaltite/gersdorffite, four grains were quantitatively analyzed and gave an average of 4.5 wt% Pd. A single grain (2 μm) of Pd-bearing hexatestibiopanickelite was identified in cobaltite, itself enclosed in pyrrhotite; quantitative analysis gave a Pd content of 15.9 wt%. The presence of Pd at trace levels was also observed in ullmannite, out of 35 spot analyses, the distribution of Pd is as follows: 68.6% have values <MDL, 22.9% between 0.02-0.05 and 8.6% between 0.05-0.10 with 0.09 wt% as maximum content.

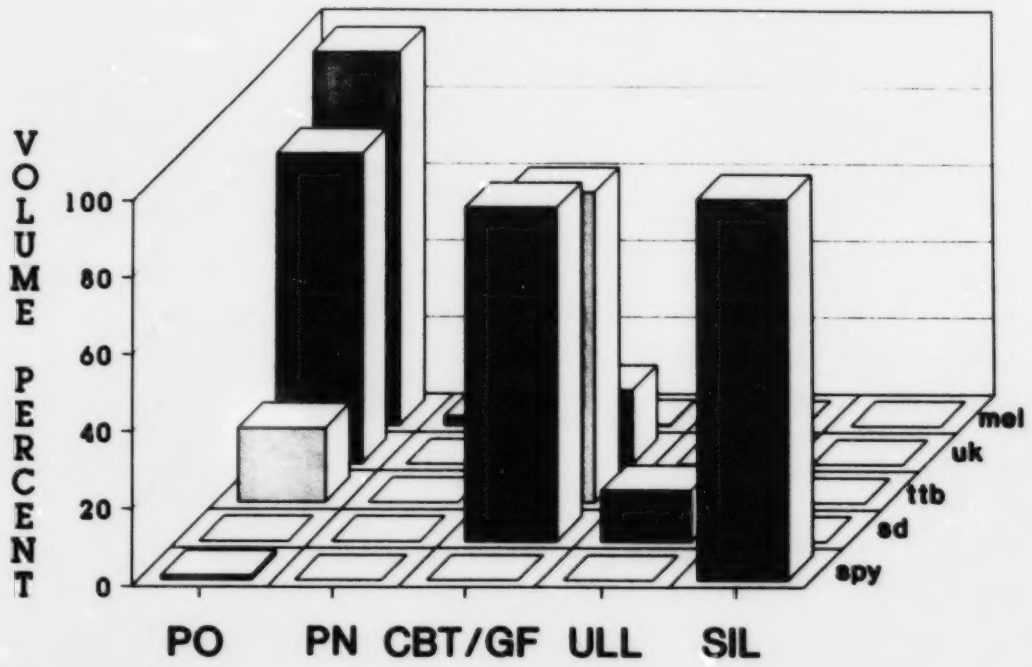

Fig. 5. Volume per cent distribution of PGM and some PGE-bearing minerals in PO=pyrrhotite, PN=pentlandite, CBT/GF=cobaltite/gersdorffite, ULL=ullmannite, and SIL=silicate gangue. Sample EII, disseminated sulphides in chill gabbro.

Finally, the eight grains of an Au-Ag alloy found range from <2 to 5x10 μm, and all are included in cobaltite/gersdorffite.

Sample #1 (Typical low-grade gabbro, West zone)

The opaque base metal mineralogy consists of chalcopyrite, pentlandite, pyrrhotite >> ilmenite and pyrite. Minor to trace amounts of barite, chromite, magnetite, cobaltite/gersdorffite, arsenopyrite, siegenite, violarite, titanite, argentopentlandite, galena, altaite, hessite and Au-Ag alloy were identified. The major sulphides are quite variable in grain size but there appears to be two populations: relatively coarse-grained sulphides (up to 1-1.5 mm) and fine-grained sulphides (<5 μm) dispersed in the gangue. Electron microprobe analyses of fifteen grains of pentlandite selected at random show almost no variation with average contents of 35.45 wt% Ni (35.0-35.8) and 2.45 wt% Co (1.9-2.6). Cu was not detected, with a minimum detection level of 0.03 wt%. Fifteen randomly selected grains of pyrrhotite had a range of 0.05 to 0.52 wt% Ni and averaged 0.32 wt%. Only three grains have shown values for Cu above the MDL of 0.03 (0.20, 0.23 and 0.15), and Co was not detected (MDL of 0.03 wt%).

Amphibole (tremolite ?), serpentine, and chlorite (clinochlore) constitute the major silicates (in decreasing order), as determined by X-ray diffraction. Electron microprobe analyses were performed for Ni with an MDL of <0.015 wt.% Ni. The amphibole has a mean concentration of 0.03 wt.% Ni, taking 6 of 20 analyses with <MDL as 0. The range of values is 0.02 to 0.05 wt.% Ni, with an arithmetic mean of 0.035 wt.% Ni. The Ni content of the chlorite is higher: 0.08 wt.% Ni, with only one of ten anlyses <MDL.

Four grains of arsenopyrite and eight of cobaltite were analyzed quantitatively with the electron microprobe. Arsenopyrite averaged 0.08 wt.% Ni and cobaltite averaged 8.0 wt.% Ni.

Thirty grains of sperrylite were identified, they range in size from <2 to 60 x 60 μm; 92 vol.% are liberated, 4 vol.% are included in chalcopyrite, 4 vol.% in gangue, <1 vol.% in pyrrhotite and <1 vol.% in other PGM. Twenty-two grains of testibiopalladite were found, ranging in size from <2 to 20 x 25 μm; 91 vol.% occur in chalcopyrite, 6 vol.% in pyrrhotite and 3 vol.% in pentlandite. Ten grains of michenerite range in size between <2 to 9 x 11 μm,

with 74 vol.% included in pyrrhotite, 26 vol.% in cobaltite/gersdorffite and <1 vol.% in chalcopyrite. Two grains of hollingworthite (<2 μm, both occurring in small euhedral cobaltite grains, one enclosed in pentlandite, the other in pyrrhotite) were found. Single grains of sudburyite (2 x 3 μm in chalcopyrite), a Re>Ir>Os>Ru alloy (2 x 2 μm in cobaltite/chalcopyrite) and a Re sulphide(?) (1 x 3 μm in pentlandite) were also observed. Sixty-five grains of an undefined $(Ni,Pd)_2(Te,Sb)_3$ mineral were found, ranging in size between <2 to 25 x 80 μm, with 87.8 vol.% occurring in chalcopyrite, 7.7 vol.% in pyrrhotite and 4.5 vol.% in pentlandite. Twenty-three of these grains were quantitatively analyzed and gave an average Pd content of 11.8 wt% (3.3-23.2); also, two of these grains have Pd>Ni therefore suggesting existence of a solid solution series between $(Ni,Pd)_2(Te,Sb)_3$ and $(Pd,Ni)_2(Te,Sb)_3$. Thirteen grains of palladian-platinian melonite were also found, ranging in size between <2 to 10 x 10 μm. Its distribution is as follows: 54.7 vol.% in pentlandite, 44.7 vol.% in pyrrhotite and 0.6 vol.% in chalcopyrite. Also, one small euhedral grain of cobaltite containing Rh was observed in pentlandite (1 x 3 μm). Two small grains of Au-Ag alloys were found, one in pyrrhotite (<2 μm) and the other in cobaltite (1 x 10 μm). Figure 6 demonstrates the different mode of occurrence between Pt minerals (sperrylite) and the Pd and Pd-bearing minerals (testibiopalladite, undefined $(Ni,Pd)_2(Te,Sb)_3$, palladian melonite and sudburyite). The relatively large sperrylite grains produced dominantly liberated grains with the balance evenly distributed between chalcopyrite and silicates. The Pd and Pd-bearing minerals, while small, are concentrated in chalcopyrite.

In addition, the dominance of sperrylite over the other PGM can be shown by comparison of volumetric abundance to relative abundance, based on number of grains (Fig. 7).

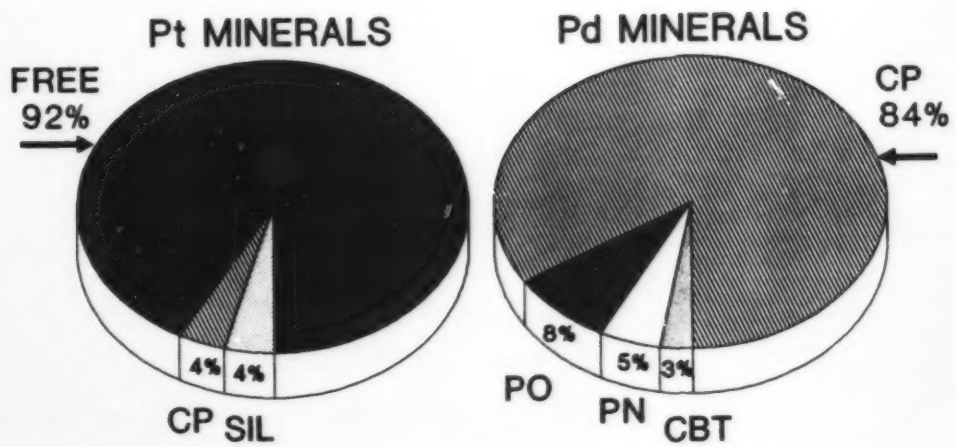

Fig. 6. Mineralogical distribution of Pt and Pd minerals in volume percent. Sample #1, typical low-grade gabbro, West zone.

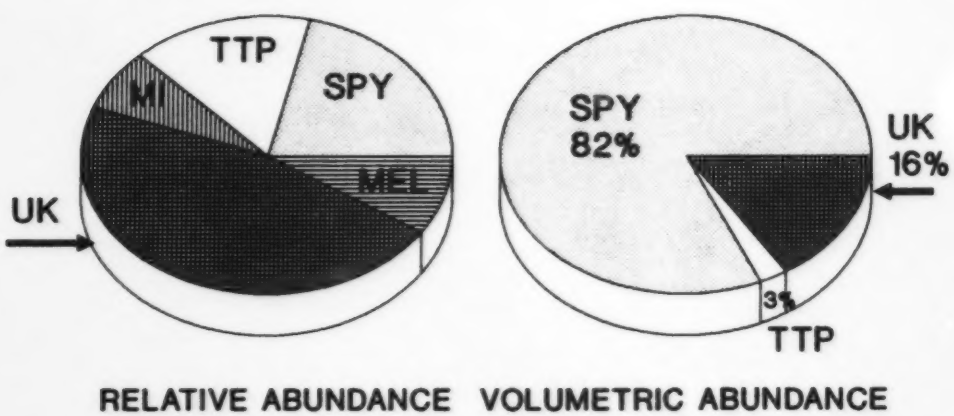

Fig. 7. Relative abundance compared to volumetric abundance. Sample #1, typical low-grade gabbro, West zone.

Sample #2 (Typical clinopyroxenite, West zone)

Chalcopyrite, ilmenite, magnetite, pentlandite and violarite are the major opaque base metal minerals in this sample. Minor to trace amounts of pyrite, chromite, pyrrhotite, sphalerite, barite, arsenopyrite, cobaltite-gersdorffite, argentopentlandite, galena, altaite, breithauptite, hessite and Au-Ag alloy were identified. As observed in sample #1, the major sulphides are quite variable in grain size and once more, there appears to be two populations: relatively coarse-grained sulphides (up to ~1 mm) and fine-grained sulphides (<5 μm) dispersed in the gangue. Very little grain to grain variation was observed in pentlandite; electron microprobe analyses of fifteen grains selected at random gave average contents of 33.35 wt% Ni(32.6-33.9) and 2.3 wt% Co(2.1-2.6). Cu was not detected (MDL of 0.03 wt%). Fifteen grains of pyrrhotite were also analyzed and had a range of 0.22 to 0.84 wt% Ni (av. of 0.62 wt%), Co was not detected (MDL = 0.03), while Cu was detected in only two grains with values of 0.03 and 0.06 wt%.

Sample #2 consists mainly of serpentine, with major chlorite, as determined by X-ray diffraction. The serpentine contains a mean Ni concentration of 0.066 wt.% Ni, on the basis of 50 electron microprobe analyses. The range is 0.02 to 0.30 wt.% Ni and the median value is 0.04 wt.% Ni.

Although extremely fine-grained, a large number of highly diversified PGM or PGE-bearing minerals were found in this sample. Sperrylite is by far the most important of all, since one hundred and fifty-six particles were identified, ranging in size between <2 to 9 x 10 μm; 60 vol.% of these grains are included in magnetite, 17 vol.% in pentlandite, 14 vol.% in gangue, 6 vol.% in violarite and 3 vol.% in chalcopyrite. The forty-seven grains of sudburyite range in size between <2 to 8 x 13 μm and 58 vol.% are included in chalcopyrite, 24 vol.% in magnetite, 9 vol.% in pentlandite, 7 vol.% in gangue and 2 vol.% in pyrrhotite. Nineteen grains identified as michenerite were also observed, ranging in size between <2 to 8 x 21 μm, 73 vol.% occur in pentlandite, 14 vol.% in magnetite, 10 vol.% in chalcopyrite and 3 vol.% in gangue. Four grains of a Pt-Fe alloy (<2 to 3 x 3 μm) all associated with magnetite, three grains of hollingworthite (2 x 4 to 1 x 12 μm), one in gangue and two in magnetite, two grains of testibiopalladite (1 x 7 μm in pentlandite, 1 x 4 μm in chalcopyrite), two grains of

stibiopalladinite (1 x 2 and 1 x 5 μm) and two grains of laurite (1 x 2 and 2 x 3 μm), all included in magnetite. Single grains of moncheite (2 x 4 μm) and an undefined Pd-Hg mineral (1 x 3 μm) in magnetite, geversite (2 x 3 in pentlandite), and iridium (0.5 x 3 μm with other PGM in gangue) were also identified.

The PGE-bearing minerals consist of two undefined minerals [$(Ni,Pd)_2(Te,Sb)_3$] and [$(Ni,Pd)_3(Te,Sb)_4$], melonite [$(Ni,Pd)Te_2$], breithauptite [(Ni,Pd)Sb] and to a lesser extent, violarite, pyrrhotite and chalcopyrite. A total of thirty-three grains of the two undefined minerals were found, ranging in size between <2 to 12 x 20 μm. In terms of volumetric distribution, these minerals which contain an average of 14 wt% Pd, 67% were found in magnetite, 18% in chalcopyrite, 13% in pentlandite and 2% in pyrrhotite. Five grains of melonite range in size from <2 to 3 x 5 μm; three occur in pentlandite, one in pyrrhotite and the other in chalcopyrite. Several small grains (<10 μm) of breithauptite were observed associated with magnetite, with Pd content ranging between 2 and 19 wt%. Trace amounts of Pd and Ru were detected by proton microprobe analyses in some major sulphide minerals (violarite, pyrrhotite and chalcopyrite). Gold occurs in the form of a gold-silver alloy, of which twenty-seven grains were located. They range in size between <2 to 5 x 10 μm, with 93% occurring in chalcopyrite, and 7% in gangue.

All the PGM are strongly associated with magnetite in this sample. In the case of sperrylite, the only Pt mineral, even the grains included in pentlandite or chalcopyrite are often themselves enclosed by magnetite. These relationships are shown in Figure 8.

Sample #3 (Typical clinopyroxene-rich peridotite - East zone)

Chalcopyrite, pyrrhotite and magnetite are the major opaque minerals in this sample. Minor to trace amounts of pentlandite, violarite, pyrite, chromite, ilmenite, sphalerite, barite, arsenopyrite, cobaltite-gersdorffite, covellite, galena, ullmannite and Au-Ag alloy were identified. As observed in the previous two samples (1 and 2), the major sulphides are variable in grain size and there appears to be two populations. Relatively coarse-grained sulphides (up to 0.5 mm) which are often associated with magnetite and fine-grained sulphides (<5 μm) dispersed in serpentine. Fifteen grains of pentlandite selected at random from a heavy mineral

separate, were quantitatively analyzed and only show minor grain to grain variation. Average contents of 35.7 wt% Ni(34.7-36.1) and 1.8 wt% Co(1.7-1.9) were obtained. Cu was not detected (MDL of 0.03 wt%). Thirteen grains of pyrrhotite, also selected at random from a heavy mineral separate were also analyzed, and gave average content of 0.57 wt% Ni(0.50-0.62). Traces of Cu were detected (<0.03-0.11 wt%) and Co was sought for but not detected (MDL = 0.03 wt%).

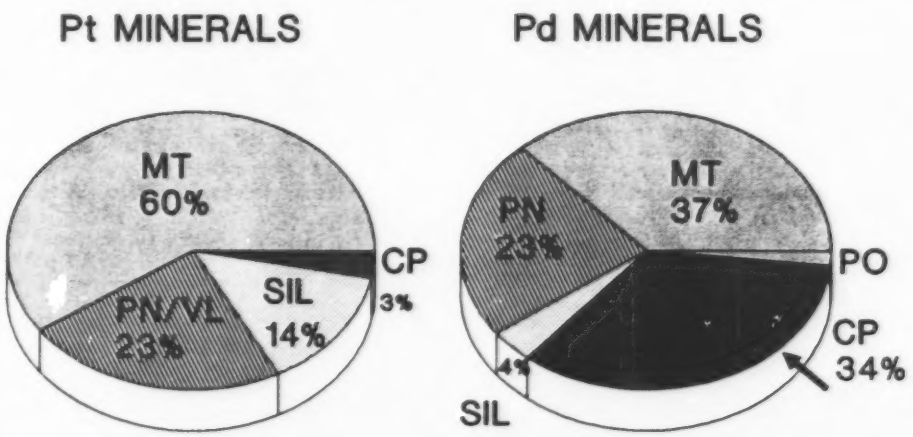

Fig. 8. Mineralogical distribution of Pt and Pd minerals (vol.%) for sample #2.

As for sample #2, this sample consists mainly of serpentine, with minor chlorite. Electron microprobe analyses of 50 serpentine grains ranged from <MDL to 0.13 wt.% Ni and an arithmetic mean of 0.066 wt.% Ni. The median value is slightly higher, at 0.075% Ni. Where analyses were <MDL, 0 was used for the averaging, as was done for sample #1.

As observed in sample #2, the PGM and PGE-bearing minerals are extremely fine-grained. Twenty-six grains of sudburyite were identified, they range in size from <2 to 4 x 6 μm with 36 vol.% included in pentlandite/violarite, 30 vol.% in pyrrhotite, 20 vol.% in chalcopyrite and 14 vol.% in magnetite. The twenty grains of sperrylite identified range from

<2 to 3 x 10 μm in size; 77 vol.% are included in magnetite, 10 vol.% in pentlandite/violarite and 13 vol.% in chalcopyrite. Three grains of stibiopalladinite were observed in pentlandite/violarite (<2 to 2 x 7 μm), two grains of an undefined $(Pd,Ni)_5(Te,Sb)_4$ mineral, one in chalcopyrite and the other in pentlandite, both measuring 1 x 2 μm were also identified. A single grain of merenskyite was found in magnetite (5 x 6 μm).

The PGE-bearing minerals include an unknown mineral $[(Ni,Pd)_3)(Te,Sb)_4]$, melonite $[(Ni,Pd)Te_2]$, and to a lesser extent, violarite, pyrrhotite and chalcopyrite. A total of twenty grains of the unknown mineral were found, ranging in size from <2 to 4 x 6 μm. The distribution of this mineral, which contains an average of 14.9 wt% Pd, is as follows: 33 vol.% in pyrrhotite, 30 vol.% in chalcopyrite, 27 vol.% in pentlandite/violarite and 10 vol.% in magnetite. A single grain of melonite (3 x 3 μm) was found at pyrrhotite/magnetite boundary. Trace amounts of Pd and Ru were detected by proton microprobe analyses in some major sulphide minerals (violarite, pyrrhotite and chalcopyrite). In addition, sixteen grains of Au-Ag alloy were located. They range in size from <2 to 7 x 20 μm and occur in sulphides (pentlandite/violarite, chalcopyrite and pyrrhotite). The dominant association of the Pt-minerals (i.e. sperrylite) with magnetite is in contrast to the Pd-minerals, which are mainly included in sulphides (Figure 9).

(b) Image analysis

Quantitative image analysis was applied to -35+65 mesh fractions of samples #1, #2, and #3, using the MP-SEM-IPS, to determine size distributions of the major opaque minerals (chalcopyrite, pentlandite + violarite, pyrrhotite, and magnetite). This was done because two size populations are apparent in qualitative ore microscopic examination.

Image analysis was complicated by the fact that two mineral pairs (pentlandite + chalcopyrite and pyrrhotite + violarite) have average atomic numbers that are too close to each other when using the backscattered electron image (BEI) as the sole method of mineral discrimination. Phase discrimination was performed by producing BEI of both pairs and using Ni X-ray maps to define the pentlandite and the violarite. Thus, the pentlandite was subtracted

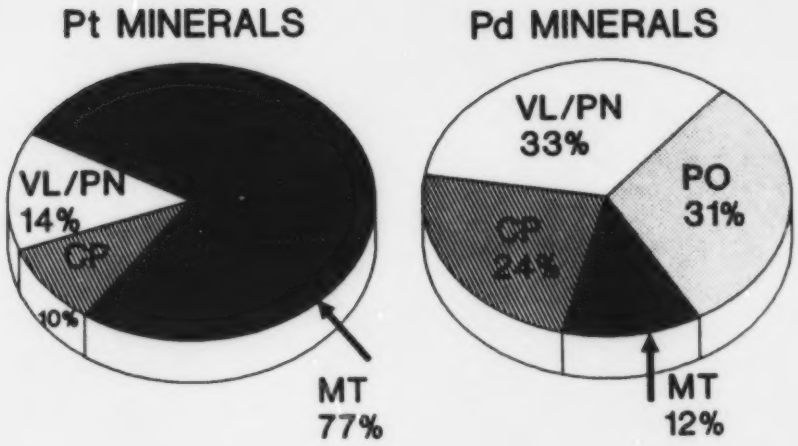

Fig. 9. Mineralogical distribution of Pt and Pd minerals, in volume percent. Sample #3, typical clinopyroxenite, East zone.

from the pentlandite + chalcopyrite image and violarite from the pyrrhotite + violarite image. However, this procedure for mineral discrimination has its drawbacks as it is extremely slow.

Figures 10 to 13 summarize the size distributions for pentlandite (plus violarite), chalcopyrite, pyrrhotite, and magnetite. The X-axis of the figures gives the grain-size in micrometers of the mineral of interest in terms of equivalent diameter; the Y-axis gives the cumulative weight per cent finer than a given size.

The size distribution curves for the three samples are very similar in the case of pentlandite plus violarite (Fig. 10). The only variation observed indicates that sample #1 is finer grained at K_{80}, i.e., 80% of pentlandite plus violarite is finer than 54 μm whereas 80% of pentlandite plus violarite is finer than about 80 μm for samples #2 and 3.

The differences in size distribution for chalcopyrite in the 3 samples is not large (Fig. 11), except that chalcopyrite in sample #3 is clearly finer-grained than in the other two. K_{80} for sample #3 is 55 μm whereas it is about 90 μm in the other two samples. Pyrrhotite, on the other hand varies considerably in size distribution (Fig. 12). Pyrrhotite in sample #2 is

considerably more fine-grained than in the other two samples. Magnetite also shows some difference in its size distribution between the 3 samples (Fig. 13).

The general size-distribution parameters for all 3 samples are given in Table 5. Of interest is weight per cent finer than 500 mesh. Firstly, 30 wt.% pentlandite + violarite is equally finer than 500 mesh for all three samples. In contrast to this, 50 wt.% of the chalcopyrite for sample #3 is -500 mesh, compared with 28 wt.% for samples #1 and #2. Pyrrhotite in sample #2 has 60 wt.% -500 mesh compared with 33 wt.% for sample #3 and only 8 wt.% for sample #1. In the case of magnetite, sample #2 is finer-grained, with 36 wt.% -500 mesh. Considering all five minerals collectively for the samples as a whole, sample #2 is finer-grained, followed by sample #3 and with sample #1 the coarsest-grained.

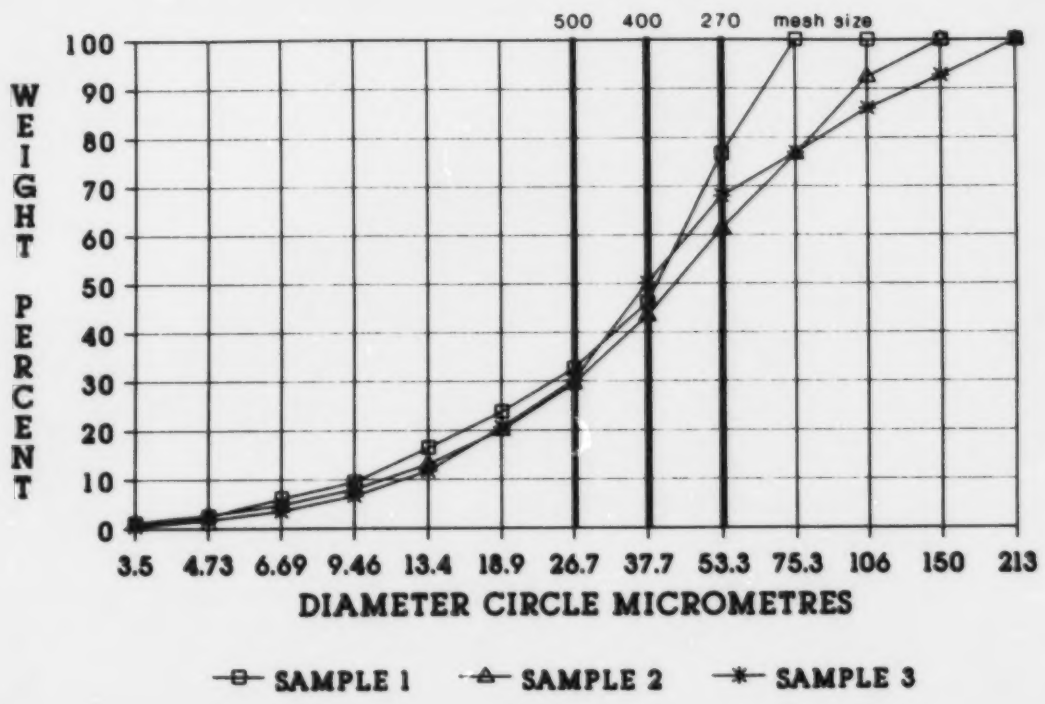

Fig. 10. Size distribution of pentlandite plus violarite in -35+65 mesh samples.

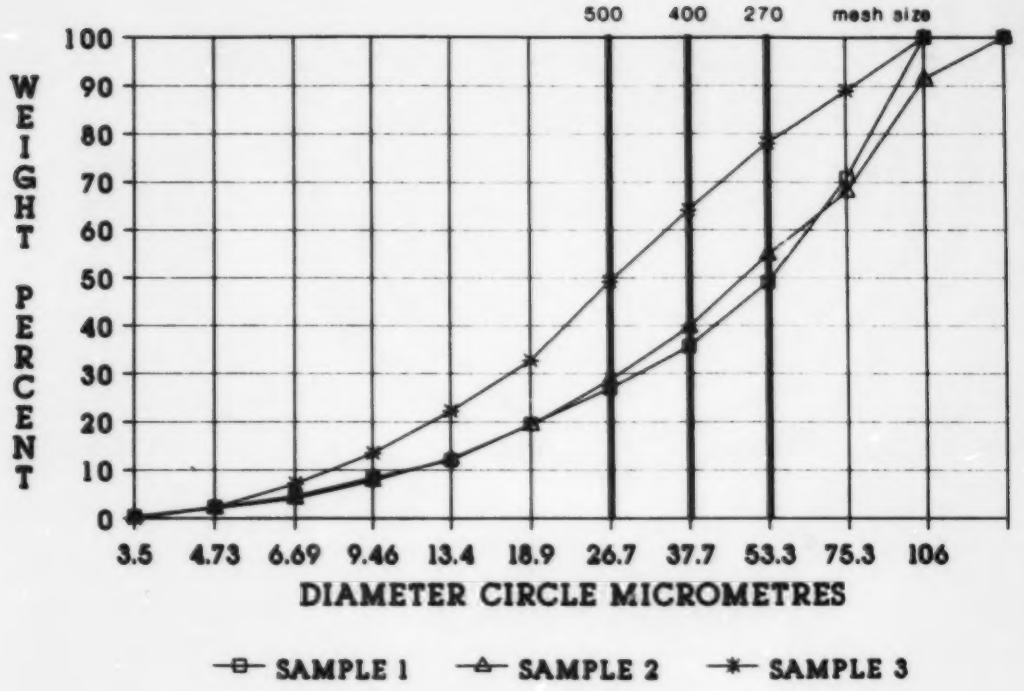

Fig. 11. Size distribution of chalcopyrite in -35+65 mesh samples.

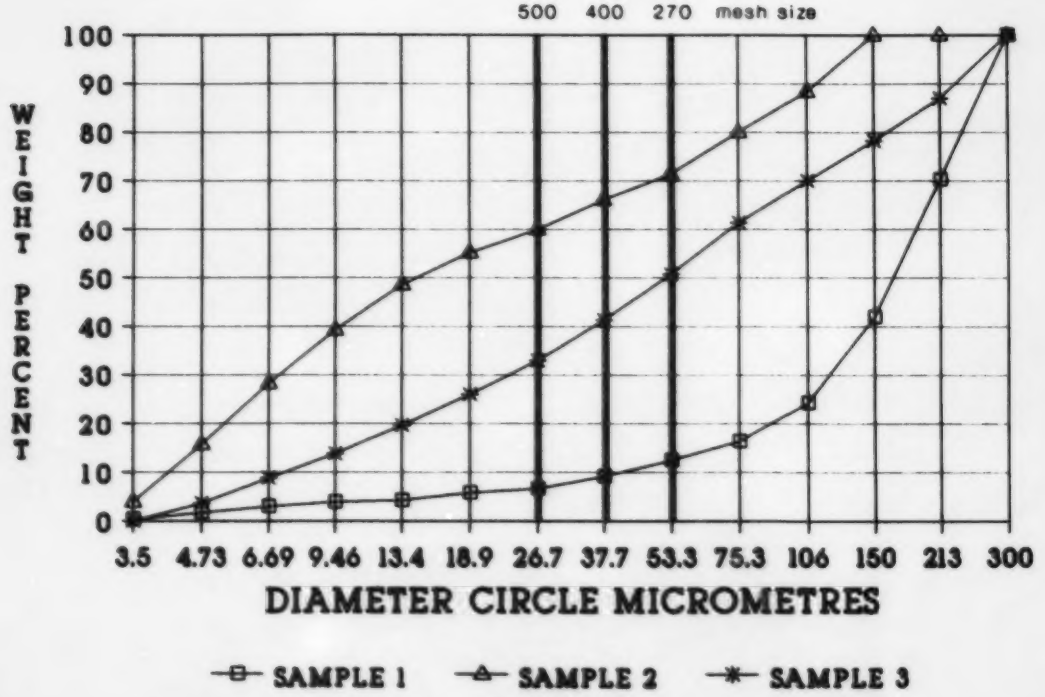

Fig. 12. Size distribution of pyrrhotite in -35+65 mesh samples.

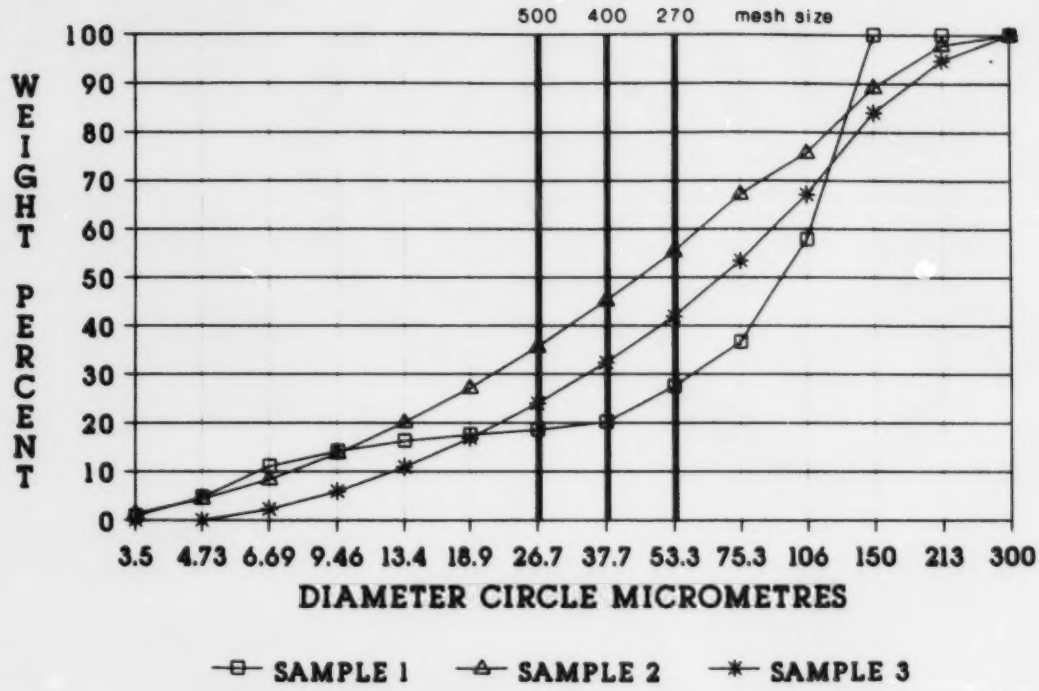

Fig. 13. Size distribution of magnetite in 35+65 mesh samples.

Table 5. Some size distribution values for samples #1, #2, #3

Samples		#1	#2	#3
K_{80} [μm]	pent.+viol.	54	80	80
	chalcopyrite	90	90	55
	pyrrhotite	250	75	150
	magnetite	150	150	150
K_{20} [μm]	pent.+viol.	19	19	20
	chalcopyrite	19	19	13
	pyrrhotite	75	5	13
	magnetite	37	13	19
wt.% at -500 mesh	pent.+viol.	~30	~30	~30
	chalcopyrite	~28	~28	~50
	pyrrhotite	~ 8	~60	~33
	magnetite	~19	~36	~24

(c) Trace element analyses

Some platinum-group element deposits contain a certain proportion of the total PGE as a dilute solid solution in some of the major sulphide minerals (Cabri & Naldrett, 1984). Because the concentration of the PGE is often below detection levels that may be easily achieved with an electron microprobe, other analytical methods have to be used. The proton microprobe has proved useful in determining low levels of at least three of the PGE : Pd, Rh and Ru (Cabri et al., 1984).

The proton microprobe was used to quantitatively analyze pentlandite, chalcopyrite and pyrrhotite for trace elements, in particular for Pd, Rh, and Ru. Minimum detection limits varied, due to changes applied to analytical conditions because the analyses were done during separate analytical periods spread over a period of nearly two years. The MDL for these 3 elements was generally in the range 4-7 ppm. Not unexpectedly, the principal carrier of Pd, Rh and Ru is pentlandite and the highest values obtained were for samples #1 and DNTS which averaged 11.4 $\pm$ 3.0 ppm Pd (range 6.3 - 15.8) and 11.1 $\pm$ 2.8 ppm Pd (range 5.7 - 16.4), respectively. Micro-PIXE results for Se, Ru, Rh, and Pd in pentlandite are summarized in Table 6. Some grains had small quantities of other elements, with maximum values given in parentheses: As(290), Ga(12), Ge(7), Ag(11), In(9), Sn(13), Sb(45), Te(122). The standard deviations reflect both the homogeneity and the precision of the analyses. High standard deviations are also due to the fact that they include many analyses where the concentration of a particular element is less than the MDL and these were taken as 0. For example, for the 20 analyses done on sample A, six had Ru from 5.7 to 12.6 ppm, the balance were 0; five had Rh from 5.3 to 11.7 ppm, the balance were taken as 0; and ten had Pd from 7.5 to 34, the other ten were taken as 0. Analyses given as a dash had too few concentrations above the MDL to indicate a meaningful number.

Table 6. Micro-PIXE analyses of pentlandite/violarite (ppm)

Sample	n	Se		Ru		Rh		Pd	
		avg.	std σ	avg.	std σ	avg.	std σ	avg.	std σ
#1	15	445	± 71	-	-	-	-	11.4	± 3
#2	9	246	± 48	-	-	-	-	-	-
#3	5	284	± 85	3.9	± 3	4.0	± 3	3.9	± 5
A	20	123	± 21	2.8	± 4	2.6	± 4	7.1	± 9
D1	10	162	± 31	-	-	-	-	6.9	± 4
DNTS	8	130	± 5	-	-	-	-	11.1	± 3
WG-1	9	106	± 6	-	-	-	-	4.8	± 4

Table 7 summarizes the Micro-PIXE analyses for chalcopyrite. Very few grains had concentrations of PGE above the MDL; e.g., one grain had 10 ppm Ru, 3 grains had Pd from 6.4 - 9 ppm, and one grain had 10 ppm Rh. Other elements were also sometime found, with maximum values in parentheses: Ga(94), Ge(15), As(19), Te(23).

Very few of these pyrrhotite grains had PGE concentrations near the MDL, only one (5.6 ppm Pd) was actually above the MDL. The principal trace element found was Se, with the following results: Sample #1 492 ppm ± 21%, Sample #2 225 ppm ± 8%, Sample DNTS 146 ppm ± 3%. Occasionally other elements were found, with maximum values in parentheses: Ga(10), Sb(15), Te(17).

Table 7. Micro-PIXE analyses of chalcopyrite (ppm)

Sample	n	Zn		Se		Ag		Cd	
		avg.	std σ	avg.	std σ	avg.	std σ	avg.	std σ
#1	8	670	± 86	282	± 31	28.8	± 6	11.2	± 3
#2	5	674*	± 201*	218	± 24	15.0	± 8	13.8	± 2
#3	3	447	± 29	179	± 21	-	-	5.2	± 4
C	8	521	± 238	75	± 22	43.0	± 26	8.3	± 6
D1	5	546	± 128	205	± 59	-	-	14.5	± 5
* 3 analyses only									

DISCUSSION

Reserves at Wellgreen are considered to lie within gabbro and intercalated clinopyroxenite (ACA nomenclature). These are overlain by ultramafic rocks, some of which, e.g. "clinopyroxene-rich peridotite" (= sample #3) are macroscopically indistinguishable from "clinopyroxenite" (= sample #2). Commercial exploitation of the deposit depends upon successful extraction of Cu, Ni, Pd, Pt, and to a lesser extent Co, Au and the minor PGE such as Rh and Ru. This discussion, however, addresses in greater detail factors affecting recovery of Cu, Ni, Pt and Pd from samples #1, #2 and #3.

Mineralogical Distribution of Nickel

The principal Ni carriers are pentlandite, violarite, sulpharsenides, pyrrhotite, and silicates, listed in order of decreasing Ni content. Violarite, an alteration product closely associated with pentlandite, has a variable Ni content which was not determined as it is difficult to analyze quantitatively in these samples. Therefore, for purposes of calculation of the mineralogical Ni balance, violarite is included with pentlandite.

The calculated Ni distribution for sample #1 is 73.7% in pentlandite/violarite, 1.8% in pyrrhotite, 1.7% in sulpharsenides, 9.8% in serpentine, 8.9% in amphibole, and 4.0% in chlorite. The mineralogical distribution of Ni, recalculated to 100%, is given in Figure 14. Therefore, recovery of Ni is affected both by the fine grain-size of the major Ni carriers (pentlandite and violarite), as shown in Figure 10 and by the approximate 24% Ni in pyrrhotite and silicates, which cannot be liberated by finer grinding as it is contained within their crystal structures.

Modal analyses for samples #2 and #3 were severely affected by selective plucking of pentlandite and pyrrhotite during sample preparation, prior to quantitative image analysis. Adjustments were made to the modal analyses, based on a series of additional tests and the mineralogical distribution of Ni was recalculated to 100%. The calculated Ni distribution for

samples #2 and #3 is given in Figures 15, and 16, respectively. These figures are similar and indicate the relatively high proportion of Ni contained within silicate structures, which is therefore not recoverable by fine grinding.

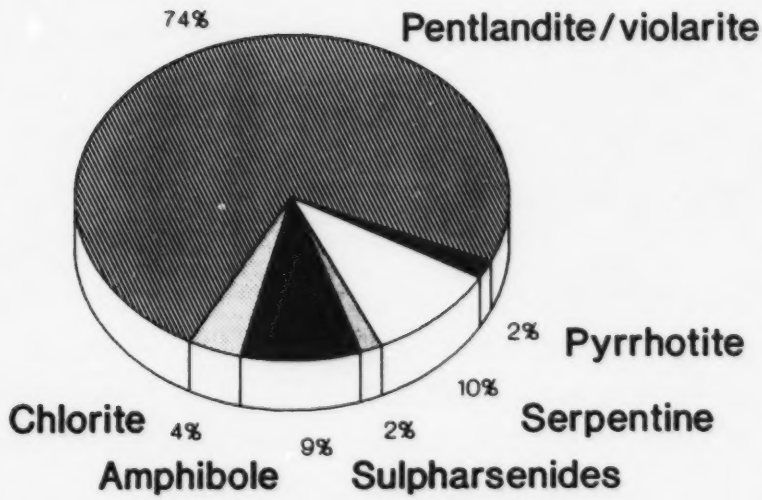

Fig. 14. Mineralogical distribution of Ni, recalculated to 100%, for sample #1. It should be noted that the major silicate (amphibole) was taken as 60 wt.% and the second most abundant silicate (serpentine) was taken as 30 wt.% and the chlorite was estimated as 10 wt.%.

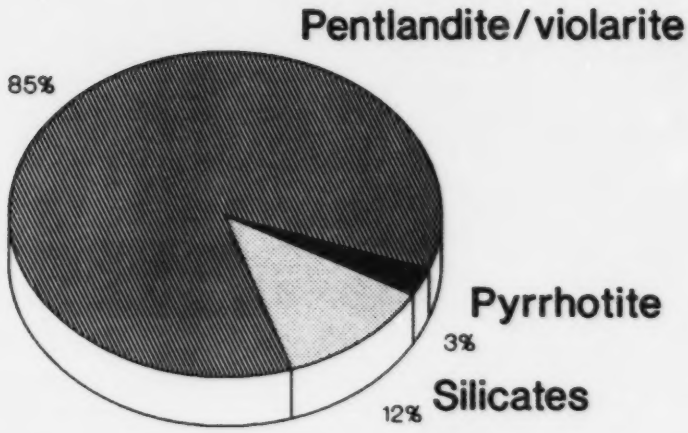

Fig. 15. Mineralogical distribution of Ni, recalculated to 100%, for sample #2. The Ni content of the serpentine (0.066 wt.%) was used for all the silicates.

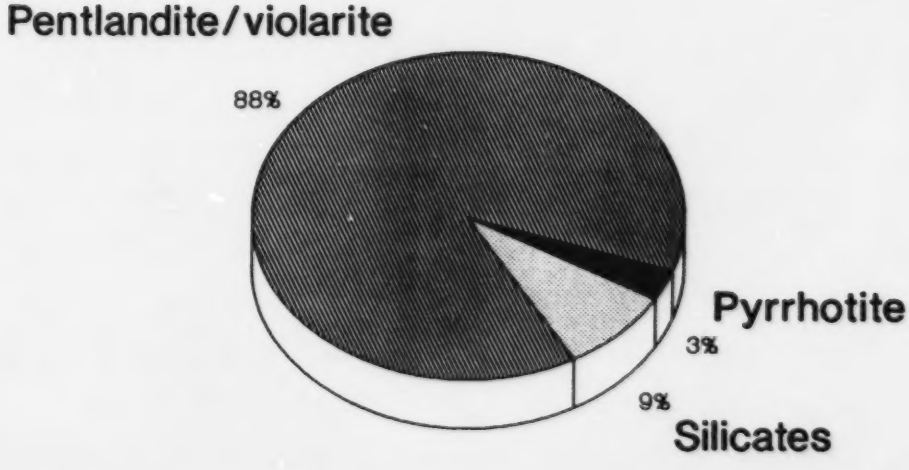

Fig. 16. Mineralogical distribution of Ni, recalculated to 100%, for sample #3. The Ni content of the serpentine (0.066 wt.%) was used for all the silicates.

Mineralogical Distribution of Copper

The copper carrier is predominantly chalcopyrite; thus its recovery will respond directly to grinding. As shown in Figure 11 and Table 5, sample #3 will require finer grinds to liberate chalcopyrite than will samples #1 and #2.

Mineralogical Distribution of Platinum

The principal Pt carrier for samples #1, #2 and #3 is sperrylite ($PtAs_2$). Sample #1 sperrylite has a size range from <2 to 60 μm in diameter. Thus, at a grind of -270 mesh over 90% of the sperrylite is liberated. Fine grinding tends to preferentially grind sperrylite as it is brittle and fractures easily. In addition, the high density of sperrylite (10.79 g/cm^3) will increase the probability of a sperrylite grain reporting to a cyclone underflow and will thus report back to the grinding mill (Kerr and Kipkie, 1985). Therefore, material such as sample #1 has to be processed in such a manner as to stress opportunities for undergrinding and underprocessing. In sample #2, the sperrylite is considerably finer-grained (<10 μm in diameter) and most of the sperrylite is locked in magnetite (60 vol.%) and in silicates (14 vol.%). Platinum recovery for sample # 2 will be low, unless some form of magnetic separation is employed. Sperrylite in sample #3 is similar in grain-size to sample #2 and has 77 vol.% locked in magnetite, hence Pt recovery will also be low, unless magnetic concentration is feasible.

Mineralogical Distribution of Palladium

Palladium carriers are variable and range from palladium minerals such as sudburyite (PdSb, with 46% Pd) through Pd-bearing Ni tellurides (e.g., melonite, with up to 15% Pd) to major sulphide minerals, which may contain very low concentrations of Pd (e.g., 34 ppm or less in pentlandite). The Pd minerals are generally less than 25 μm in diameter.

In sample #1, 84 vol.% of the Pd minerals are locked in chalcopyrite and should report to a Cu concentrate. About 22% of the total Pd occurs as a solid solution in pentlandite (at a concentration of 11.4 ppm Pd). The association of Pd minerals with chalcopyrite is only

34 vol.% in sample #2, with 37 vol.% occurring in magnetite and 23 vol.% in pentlandite. Similarly, for sample #3, 24 vol.% of the Pd minerals occur in chalcopyrite, 33 vol.% in pentlandite, 31 vol.% in pyrrhotite, and 12 vol.% in magnetite. In contrast to sample #1, only about 9% of the total Pd occurs as a solid solution in pentlandite (at a concentration of 3.9 ppm).

CONCLUSIONS

Though only six minerals may be considered to represent the major opaque minerals (pyrrhotite, pentlandite, chalcopyrite, pyrite, magnetite, ilmenite), the samples examined contained a total of approximately fifty opaque minerals. The PGE concentration is distributed between 20 different PGM, as well as between 10 other PGE-bearing minerals (including common minerals such as pentlandite and chalcopyrite). In addition, important PGM such as sperrylite occur in different size ranges among the samples examined, thus careful mineralogical study is essential prior to deciding on recovery procedures. Two rare Re minerals were also found.

The mineralogy of the ore is complex in detail, and is reflected in very diverse mineral associations among the samples examined, in particular the Phase I samples. It is therefore dangerous, if not misleading, to perform metallurgical test-work without a prior detailed understanding of the sample mineralogy, as well as its significance, in terms of the deposit as a whole.

Results of this study indicate the following:

Sample #1

Approximately 24% of the total Ni is not recoverable by grinding and conventional flotation because it is contained in the crystal structure of silicates and pyrrhotite. In general terms, if the ore is ground to 80% 26.7 μm (-500 mesh); nearly all grains larger than 37.7 μm (next higher Tyler mesh) would be liberated and 50% of grains finer than 26.7 μm would also be liberated. Therefore, applying this criteria to the data of Figure 1 (Appendix), about 70%

of the principal Ni carriers and 78% of the principal Cu carrier should be liberated at a grind of 80% -26.7 μm. Most of the Pt carrier will be liberated at a grind of 53.3 μm (-270 mesh), but the tendency of sperrylite to grind preferentially has to be monitored. Most of the Pd in this sample will report to a Cu concentrate and the balance of the Pd will be associated with pentlandite, either as Pd mineral inclusions or as a solid solution (calculated to be 22%).

Sample #2

Approximately 15% of the total Ni is not recoverable by grinding and conventional flotation because it is contained in the crystal structure of silicates and pyrrhotite. In a similar way as for sample #1, the liberation can be estimated from Figure 2 (Appendix). About 71% of the Ni carriers and 74% of the Cu carrier would be liberated at a grind of 80% -26.7 μm. Pt recovery will be poor as most Pt occurs as fine-grained sperrylite either locked in magnetite (60 vol.%) or in silicates (14 vol.%). About a third of the Pd minerals will also be lost to magnetite.

Sample #3

Approximately 12% of the total Ni is not recoverable by grinding and conventional flotation because it is contained in the crystal structures of silicates and pyrrhotite. Liberation can be estimated from Figure 3 (Appendix). About 65% of the main Ni carriers are liberated, whereas only 60% of the main Cu carrier is free at a grind of 80% -26.7μm. The bulk of the principal Pt carrier is locked in magnetite and 31 vol.% and 12 vol.% of the Pd minerals are included in pyrrhotite and magnetite, respectively. Hence, low recoveries of Pt and Pd must be expected, unless a magnetic concentrate is produced.

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APPENDIX

Size distributions given in Figures 10 to 13 have been replotted in terms of single samples and shown as Figures 1 to 3 in the Appendix. This permits inter-mineral comparisons within a particular sample.

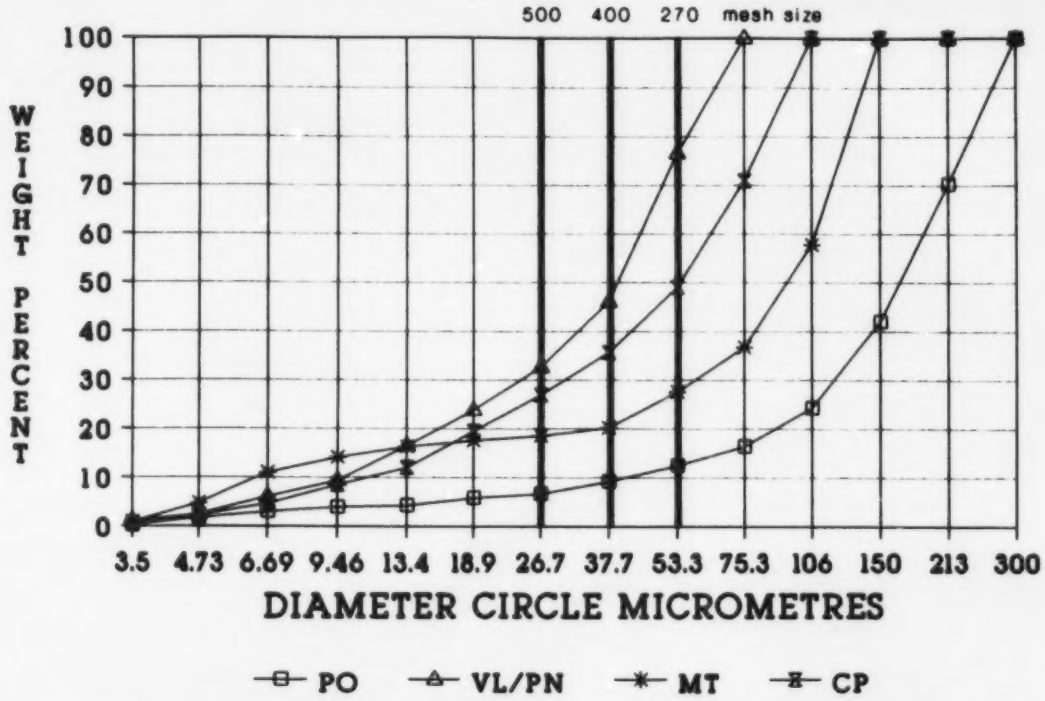

Fig. 1. Size distribution of the principal opaque minerals in sample #1 (typical low-grade gabbro, West zone).

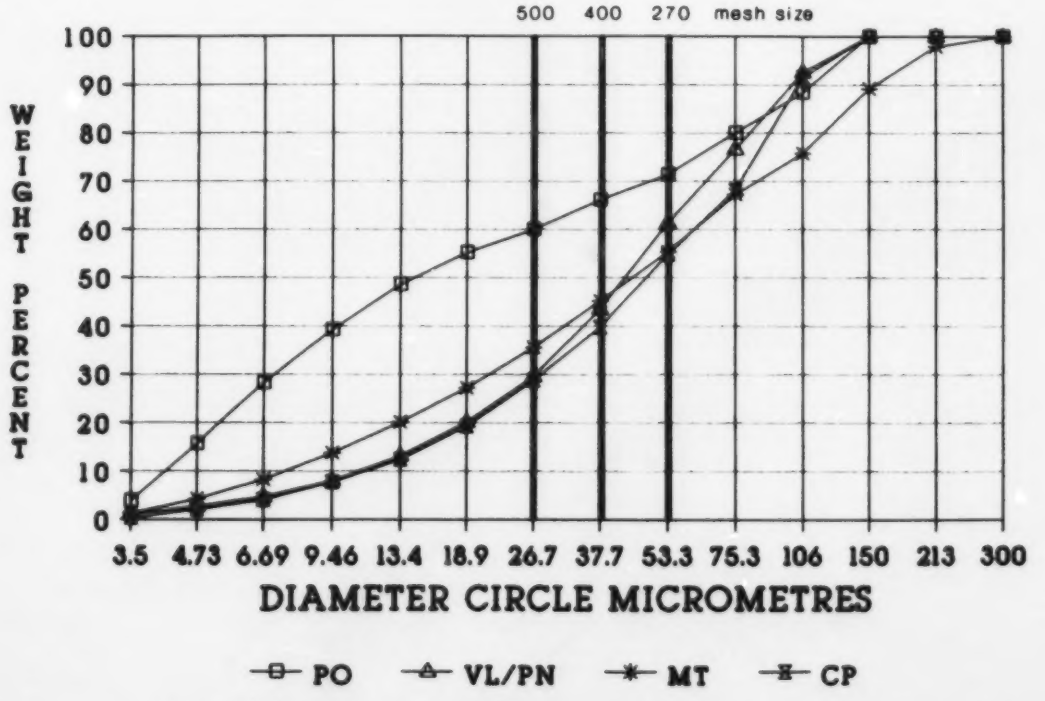

Fig. 2. Size distribution of the four principal opaque minerals in sample #2 (typical clinopyroxenite, West zone).

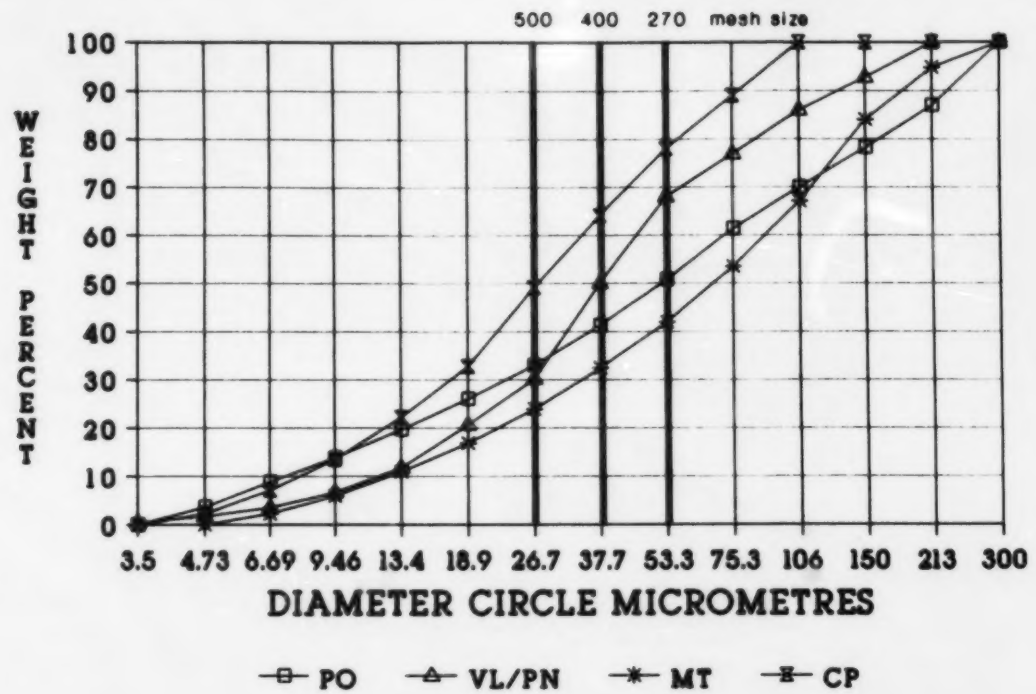

Fig. 3. Size distribution of the four principal opaque minerals in sample #3 (typical clinopyroxene-rich peridotite, East zone).